



NRL/MR/7320--00-8235

A Feasibility Demonstration of Ocean Model Eddy-resolving Nowcast/Forecast Skill Using Satellite Altimeter Data

HARLEY E. HURLBURT
ROBERT C. RHODES
CHARLIE N. BARRON
E. JOSEPH METZGER

*Ocean Dynamics & Prediction Branch
Oceanography Division*

OLE MARTIN SMEDSTAD
JEAN-FRANCOIS CAYULA

*Planning Systems, Inc.
Stennis Space Center, Mississippi*

March 10, 2000

Approved for public release; distribution unlimited.

20000620 099

REPORT DOCUMENTATION PAGE*Form Approved*
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE (DD-MM-YYYY) 10-03-2000		2. REPORT TYPE Final		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE A Feasibility Demonstration of Ocean Model Eddy-resolving Nowcast/Forecast Skill Using Satellite Altimeter Data				5a. CONTRACT NUMBER N00014-97-C-6014	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER 0603207	
6. AUTHOR(S) Harley E. Hurlburt, Ole Martin Smedstad, Robert C. Rhodes, Jean-Francois Cayula, Charlie. N. Barron, and E. Joseph Metzger				5d. PROJECT NUMBER 2342	
				5e. TASK NUMBER 105-NRL7320-001	
				5f. WORK UNIT NUMBER 73-5094-00-5	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Research Laboratory Oceanography Division Stennis Space Center, MS 39529-5004				8. PERFORMING ORGANIZATION REPORT NUMBER NRL/MR/7320—00-8235	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research 800 North Quincy Street Arlington, VA 22217-566				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT A 1/16° Pacific Ocean model north of 20°S and a 1/4° global ocean model are used to assimilate satellite altimeter data and then to perform month-long forecasts initialized from the data assimilative states. The results constitute a feasibility demonstration of ocean model eddy-resolving nowcast/forecast skill using altimeter data. In particular they demonstrate (1) that satellite altimetry is an effective observing system for mesoscale oceanic features, (2) that an ocean model with high enough resolution can be a skillful dynamical interpolator for satellite altimeter data in depicting mesoscale oceanic variability, and (3) that the high resolution ocean model can provide skillful forecasts of mesoscale variability for at least a month, when model assimilation of the altimeter data is used to define the initial state.					
15. SUBJECT TERMS Ocean data assimilation, Ocean nowcasting/forecasting, Satellite altimeter data, Eddy-resolving Pacific Ocean model, Kuroshio penetration					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES 23	19a. NAME OF RESPONSIBLE PERSON Harley E. Hurlburt
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (include area code) (228) 688-4626

ABSTRACT

A $1/16^\circ$ Pacific Ocean model north of 20°S and a $1/4^\circ$ global ocean model are used to assimilate satellite altimeter data and then to perform month-long forecasts initialized from the data assimilative states. The results constitute a feasibility demonstration of ocean model eddy-resolving nowcast/forecast skill using satellite altimeter data. In particular they demonstrate (1) that satellite altimetry is an effective observing system for mesoscale oceanic features, (2) that an ocean model with high enough resolution can be a skillful dynamical interpolator for satellite altimeter data in depicting mesoscale oceanic variability, and (3) that the high resolution ocean model can provide skillful forecasts of mesoscale variability for at least a month, when model assimilation of the altimeter data is used to define the initial state.

1. Research questions addressed by the demonstration

The figures in this report are designed to address the following questions:

1. Can satellite altimeter data be used to constrain an eddy-resolving ocean model so that it depicts the evolution of mesoscale features, such as individual current/frontal meanders and eddies?
2. Can an ocean model show skill as a dynamical interpolator for satellite altimeter data in depicting mesoscale features? Do we see a dependence on model resolution/simulation skill?
3. Can an ocean model show skill in forecasting the evolution of mesoscale features, when assimilation of altimeter data was used to define the initial state? For how long? And again what dependence do we see on model resolution/simulation skill?

2. Results of the demonstration

The remainder of this discussion is a commentary on the results in the figures used to address these questions. There are two groups of results; the first uses simulated altimeter data, the second real altimeter data. The simulated data are used to address the first question because the "truth" is precisely known, including the nonsteric mode and subsurface fields to the bottom of the model ocean. In addition, the simulated data are useful for observing system simulation experiments where the number and combination of satellite altimeters are varied. The real-data experiments are used to address questions 2 and 3.

2.1 Response to Question 1

Altimeter data were simulated by a $1/16^\circ$ six-layer Pacific Ocean model which covers the Pacific north of 20°S (Hurlburt et al., 1996b). The NRL Layered Ocean Model (NLOM) (Hurlburt and Thompson, 1980; Wallcraft, 1991; Wallcraft and Moore, 1997; Moore and Wallcraft, 1998) was used for this purpose. The $1/16^\circ$ Pacific model realistically simulates a strongly meandering Kuroshio current system and numerous eddies. The model was spun up to statistical equilibrium, then run 1990 - present forced by 12 hrly Navy Operational Global Atmospheric Prediction System (NOGAPS) winds (Hogan and Rosmond, 1991) from the Fleet Numerical Meteorology and Oceanography Center (FNMOC). The 8/90–7/97 temporal mean of these winds was replaced by the annual mean from the Hellerman and Rosenstein (1983) wind stress climatology. Then simulated altimeter data from 80 days in model year 1994 were assimilated into model year 1997, a time when the Kuroshio pathway was quite different. The corresponding 1994 winds were used during the assimilation.

Figures 1 and 2 show results 75 days into the assimilation experiment: (Fig. 1 top) the model truth field, (Fig. 1 bottom) the model with correct wind forcing for the last 75 days but no assimilation of altimeter data, (Fig. 2 top), the model with assimilation of simulated sea surface height (SSH) along Geosat 17-day repeat tracks, and (Fig. 2 bottom) with assimilation of simulated SSH along TOPEX/POSEIDON (10-day repeat), ERS-2 (35-day repeat) and Geosat ground tracks.

Figure 3 shows the rms SSH error over the whole domain and in the Kuroshio region as a function of the number of altimetric satellites available, 0 to 5 because 5 is a possibility for a period of time around the year 2001. Even one altimeter is quite effective, with the Geosat and ERS orbits giving lower error than TOPEX/POSEIDON (T/P). Reduced error is also found by having up to 3 satellites, but little further improvement is obtained by having 5 of them in this test.

Figures 4-7 show that the assimilation can constrain subsurface fields (model pressure fields for each of the six model layers), including the abyssal layer pressure field, which is only weakly correlated with the SSH field. However, the normalized rms error increases with depth.

The assimilation procedure consisted of calculating the deviations between the data along altimeter tracks that were sampled during the most recent 2 or 3 days, then performing an OI analysis once a day on this deviation data using covariance functions calculated from T/P, ERS-1/2 and GEOSAT data by Jacobs et al. (1999). For any given update much of the domain is outside the influence radius of any data and the resulting deviation analysis in those regions is zero. Next a statistical inference technique (Hurlburt et al., 1990) was used to project the deviation analysis downward (including to the abyssal layer) and geostrophy was used as a dynamical constraint away from the equator. The $1/16^\circ$ Pacific grid is $2048 \times 1344 \times 6$. Thus, it was necessary to use an efficient data assimilation technique (nudging). Related discussion can be found in Smedstad and Fox (1994), Carnes et al. (1996), Hurlburt et al. (1996a) and Smedstad et al. (1997, 1999).

2.2 Response to Question 2

This question is addressed by assimilating real T/P and ERS-2 altimeter data into (1) the same $1/16^\circ$ Pacific model and (2) a $1/4^\circ$ global model (Metzger et al., 1998). The assimilation was initialized from the model forced by FNMOC winds up to that time, at least 2 mo before 1 Jan 99. The results of the assimilation experiments are compared to $1/8^\circ$ SST analyses and purely statistical analyses of the altimeter data. The SST color scheme was chosen to highlight the Kuroshio pathway.

In two of the three experiments, the altimeter data are assimilated using the assimilative model state as the first guess for the updates with new altimeter data (which will be termed "direct assimilation" by the model). The statistical SSH analyses are independent analyses of the altimeter data which use a previous statistical analysis as the first guess. In the second $1/4^\circ$ global experiment (run by FNMOC) the daily statistical analyses were assimilated into the model. Because the earth's geoid is not adequately known, only the altimetric deviations from their own mean are used in the assimilation. In the model assimilations a slightly modified 1993-1997 model mean is added to these deviations. The statistical analyses use a 1993-1997 mean surface dynamic height from the MODAS oceanic climatology developed at NRL. When appropriately compared, these means agree closely, but the $1/16^\circ$ model mean gives a sharper depiction of mean currents.

Figures 8-12: Each figure shows panels for 1 Jan, 15 Jan and 1 Feb 1999. First compare the SSH from the data-assimilative $1/16^\circ$ Pacific model (Fig. 8) with the statistical SSH analyses (Fig. 9) and the SST analyses (Fig. 10). If given each analysis by itself, one might doubt its accuracy in depicting the mesoscale features. One might doubt the SST analyses because of data gaps due to periods of cloudiness or false fronts due to compositing of IR data over a period of time, and one would expect differences in pattern from the SSH fields because some mesoscale features lack an SST signature and because there are differences in the dynamical processes that produce SST and SSH patterns. One might doubt the accuracy of the altimetric analyses because of concerns about the space-time resolution and accuracy of the altimeter data, the mean SSH added to the altimetric deviations from their mean, and the techniques used to analyze and assimilate the data. In this case the altimeter data were analyzed by very different techniques, direct assimilation by a numerical model vs a purely statistical technique, optimum interpolation (OI). If the different analyses show agreement for mesoscale features, then each enhances the credibility of the other because it is extremely unlikely that complex agreement would occur by chance.

There are a large number of features that can be compared. Particularly noteworthy are (1) the sharp meander between 155°E and 160°E on January 1 which pinches off an eddy on 15 January in a distinctive fashion, an eddy which begins to interact with the Kuroshio farther to the west by 1 Feb. This sequence is captured with striking agreement in all three sets of analyses. (2) A second noteworthy feature is the pinch off of a large eddy immediately east of Japan (centered near 36°N , 143°E) by Feb 1st, starting from a state (see 1 January) where there is a cold eddy south of the Kuroshio just east of Japan (centered near 33.5°N , 144°E). That event is not evident in the SST analysis, but it is a feature of the operational SST analyses performed independently by the Naval Oceanographic Office (Fig. 13).

Figures 11 and 12 show corresponding results from the $1/4^\circ$ global model. In figure 11 altimeter data were assimilated directly in exactly the same manner (including the same covariance functions) as the $1/16^\circ$ Pacific model. In figure 12 the "MODAS" OI SSH analyses were assimilated into the model. While figures 11 and 12 capture most of the main features seen in figures 8 and 9, the features are not as sharp. The broadening of the Kuroshio means the current speeds are lower and dynamically the current is not as inertial, which could have a substantial impact on model forecast skill and skill as a dynamical interpolator. Comparison of figures 8 and 11 clearly shows that the $1/4^\circ$ model is not nearly as skillful a dynamical interpolator as the $1/16^\circ$ model. This is consistent with the much greater simulation skill found in purely atmospherically-forced simulations for this region using a $1/16^\circ$ vs a $1/4^\circ$ model (Hurlburt et al., 1997; Hurlburt and Metzger, 1998).

2.3 Response to Question 3

Figures 14-17 show the results of 14 and 31-day forecasts from 1 Jan 1999 which correspond to the analyses shown in figures 8-12. It should be noted that these are the very first forecasts performed using these models (not the best of many forecasts). Figure 14 shows the forecast from the $1/16^\circ$ Pacific model, figure 15 from the $1/4^\circ$ global model with direct assimilation of the altimeter data and figure 16 from the $1/4^\circ$ model with "MODAS" OI analysis assimilation. Between 155°E and 160°E the $1/16^\circ$ model is able to forecast the distinctive eddy pinch off (15

Jan) and subsequent interaction with the stream (1 Feb) in detail. It is also able to forecast the large eddy pinch off just east of Japan seen on 1 Feb. Neither of the $1/4^\circ$ forecasts succeeds in forecasting these events. Figure 17 shows three $1/16^\circ$ Pacific model forecast verifications against the model with assimilation. All show $1/16^\circ$ model forecast skill better than climatology or persistence (a forecast of no change from the initial state) for at least a month.

In these forecasts the FNMOC winds were used for the duration of the forecast, when they would not be available for a real-time forecast. In the simulated data tests (response to question 1) the model evolution in the Kuroshio region shows low sensitivity to the details of the atmospheric forcing on this time scale (because the variability in this region is largely not a deterministic response to atmospheric forcing on the forecast time scale), but obviously the effects of atmospheric forcing on oceanic forecast skill must be a subject of future testing.

3. Summary

In this study we have addressed three issues: (1) the capability of satellite altimetry as an observing system for mesoscale oceanic variability, (2) ocean model skill as a dynamical interpolator for satellite altimeter data in depicting mesoscale oceanic variability, and (3) the potential for skillful forecasting of mesoscale variability using models with assimilation of satellite altimeter data as the initial state. In particular, we addressed three specific questions:

1. Can satellite altimeter data be used to constrain an eddy-resolving ocean model so that it depicts the evolution of mesoscale features such as individual current/frontal meanders and eddies?

Obviously the answer to question 1 is yes. Substantial skill at the mesoscale is obtained using even one altimeter with the Geosat and ERS orbits preferable to the T/P orbit, but errors can be reduced significantly by using up to three satellites.

2. Can an ocean model show skill as a dynamical interpolator for satellite altimeter data in mapping mesoscale features? Do we see a dependence on model resolution/simulation skill?

Clearly the answer to question 2 is yes for the $1/16^\circ$ Pacific model which shows substantially greater skill for mesoscale features than the $1/4^\circ$ model. In general, the $1/16^\circ$ Pacific model shows much greater simulation skill for mesoscale variability and inertial currents like the Kuroshio, when the model is spun up for many years to statistical equilibrium with atmospheric forcing only.

3. Can an ocean model show skill in forecasting the evolution of mesoscale features when the model assimilates altimeter data to define the initial state for the forecast? What is the time scale for forecast skill? And again what dependence do we see on model resolution/simulation skill?

The answer to question 3 is yes for the $1/16^\circ$ Pacific model with mesoscale forecast skill for at least a month, and much greater mesoscale forecast skill than the $1/4^\circ$ model.

The results presented here should be regarded as preliminary. The forecasts shown here are the very first performed by these models (not the best of many) and there is ample opportunity to improve the data assimilation.

Acknowledgements

This work is a contribution to the 6.2 project Basin-scale Ocean Prediction System funded by the Office of Naval Research under program element 62435N and to the 6.4 projects Large Scale Ocean Modeling and Ocean Data Assimilation funded by SPAWAR. Most of the computations were performed on the Cray T3E at the Naval Oceanographic Office (NAVO), Stennis Space Center, Mississippi using Challenge and non-challenge grants of computer time from the DoD High Performance Computing Modernization Office. Near real time altimeter data were provided by the Altimeter Data Fusion Center (ADFC) at NAVO. The real-time altimeter data capability was developed jointly by the NAVO/ADFC, the NASA Jet Propulsion Laboratory, the NOAA Laboratory for Satellite Altimetry and Delft University. We thank Alan Wallcraft for his contributions in model development, portable, scalable computer code development and computational expertise. We also thank Gregg Jacobs and Kirk Whitmer for their work with the altimeter data and Jay Shriver for his contributions to this effort.

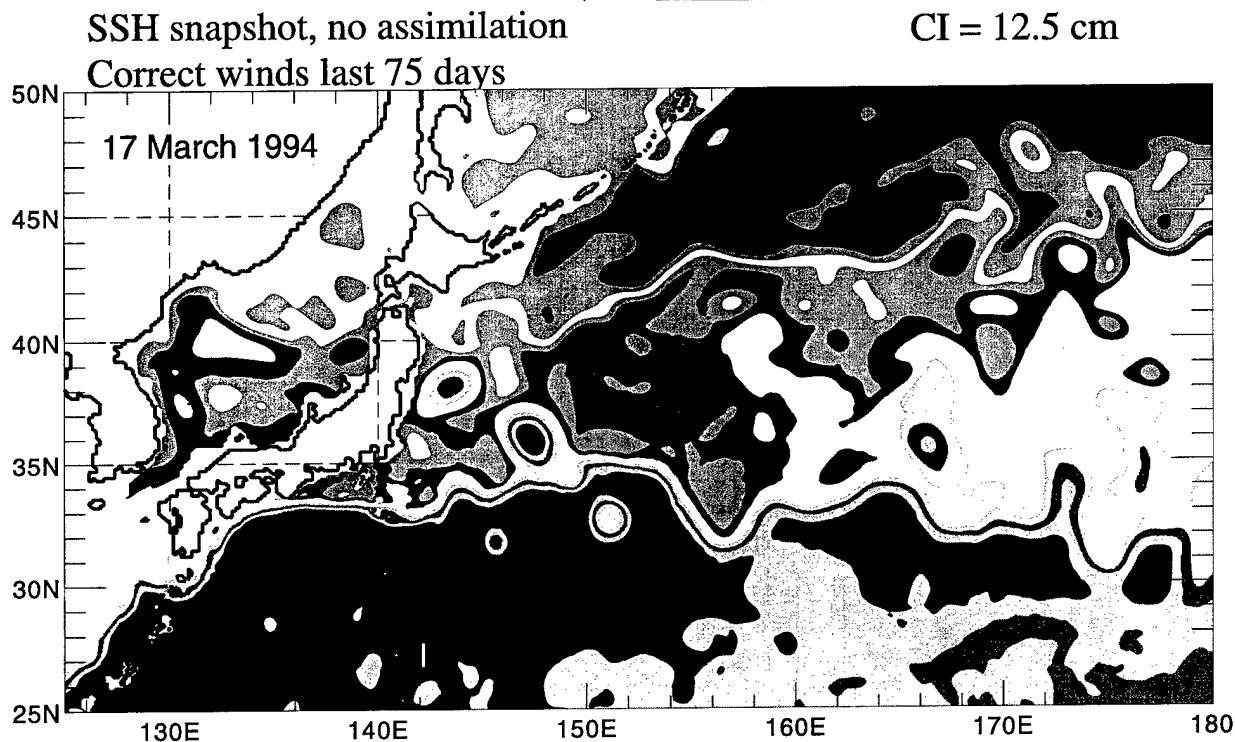
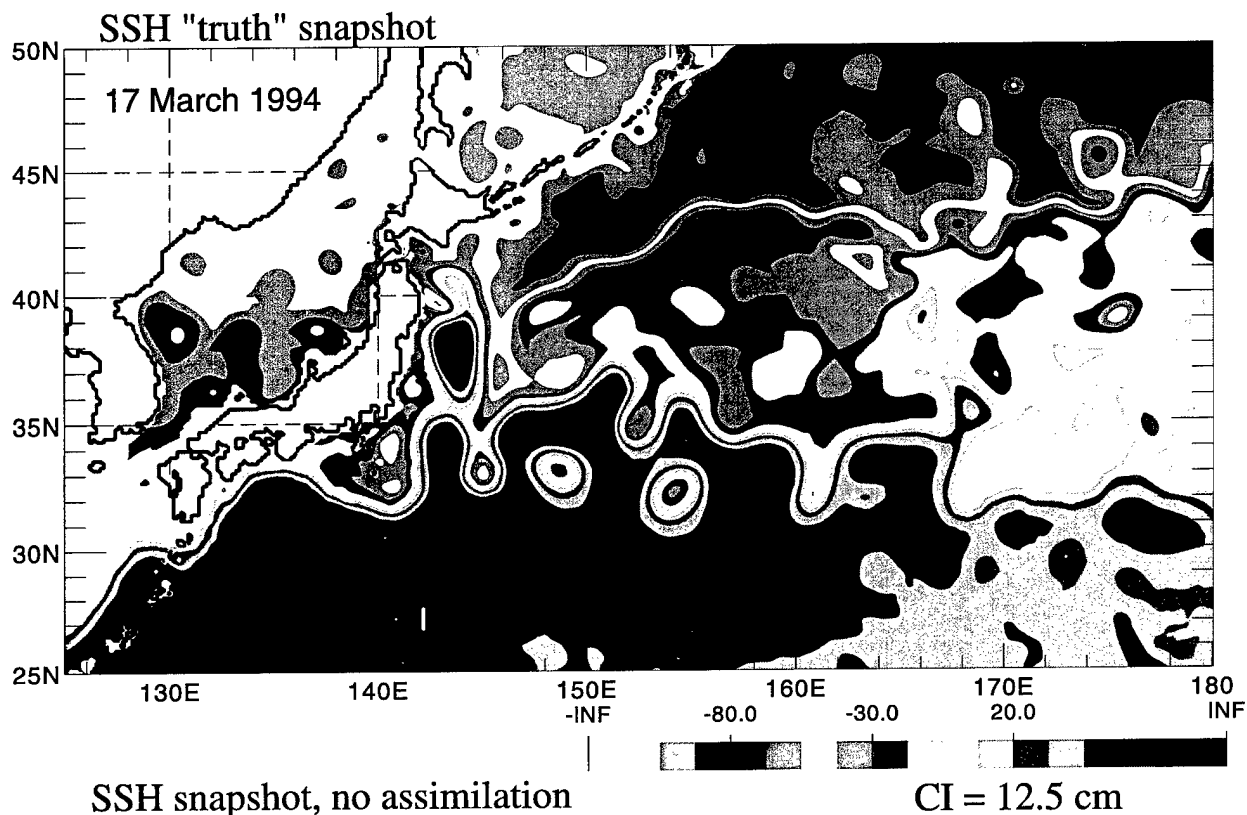
References

- Carnes, M.R., D.N. Fox, R.C. Rhodes, and O.M. Smedstad, 1996: Data assimilation in a North Pacific Ocean monitoring and prediction system. *Modern Approaches to Data Assimilation in Ocean Modeling*, Ed. by P. Malanotte-Rizzoli, Elsevier, Vol.61, pp. 319-345.
- Hellerman, S. and M. Rosenstein, 1983: Normal monthly wind stress over the world ocean with error estimates. *J. Phys. Oceanogr.*, 13, 1093-1104.
- Hogan, T. and T.E. Rosmond, 1991: The description of the Navy Operational Global Atmospheric Prediction System's spectral forecast model. *Mon. Wea. Rev.*, 119, 1786-1815.
- Hurlburt, H.E. and E.J. Metzger, 1998: Bifurcation of the Kuroshio Extension at the Shatsky Rise. *J. Geophys. Res.*, 103, 7549-7566.
- Hurlburt, H.E. and J.D. Thompson, 1980: A numerical study of Loop Current intrusions and eddy shedding. *J. Phys. Oceanogr.*, 10, 1611-1651.
- Hurlburt, H.E., D.N. Fox, and E.J. Metzger, 1990: Statistical inference of weakly correlated subthermocline fields from satellite altimeter data. *J. Geophys. Res.*, 95, 11375-11409.
- Hurlburt, H.E., M.R. Carnes, D.N. Fox, E.J. Metzger, O.M. Smedstad, and A.J. Wallcraft, 1996a: Eddy-resolving ocean modeling and prediction in the Pacific Ocean with assimilation of

- satellite altimeter and IR data. Actes du Colloque Oceanographie Operationnelle et Observation Spatiale, Biarritz, France, Meteo France, CNES, SMF, pp. 105-119.
- Hurlburt, H.E., A.J. Wallcraft, W.J. Schmitz Jr., P.J. Hogan, and E.J. Metzger, 1996b: Dynamics of the Kuroshio/Oyashio current system using eddy-resolving models of the North Pacific Ocean. *J. Geophys. Res.*, 101, 941-976.
- Hurlburt, H.E., E.J. Metzger, and P.J. Hogan, 1997: The impact of upper ocean - topographic coupling on the Kuroshio pathway south and east of Japan. *International WOCE Newsletter*, Number 25, pp.19-25.
- Jacobs, G.A., C.N. Barron, and R.C. Rhodes, 1999: The mesoscale scale. *J. Geophys. Res.* (submitted)
- Metzger, E.J., H.E. Hurlburt, J.C. Kindle, R.C. Rhodes, G.A. Jacobs, J.F. Shriver, and O.M. Smedstad, 1998: The 1997 El Niño in the NRL Layered Ocean Model. *1998 NRL Review*, Nav. Res. Lab., Washington, DC, pp. 63-71.
- Moore, D.R. and A.J. Wallcraft, 1998: Formulation of the NRL Layered Ocean Model in spherical coordinates. Nav. Res. Lab., Stennis Space Center, Miss, NRL CR 7323—96-0005, 24 pp.
- Smedstad, O.M. and D.N. Fox, 1994: Assimilation of altimeter data in a two-layer primitive equation model of the Gulf Stream. *J. Phys. Oceanogr.*, 24, 305-325.
- Smedstad, O.M., D.N. Fox, H.E. Hurlburt, G.A. Jacobs, E.J. Metzger, and J. Mitchell, 1997: Altimeter data assimilation into a $1/8^\circ$ eddy resolving model of the Pacific Ocean. *J. Met. Soc. Japan*, 75, 429-444.
- Smedstad, O.M., J.F. Cayula, H.E. Hurlburt, R.C. Rhodes, and C.N. Barron, 1999: Assimilation of satellite altimeter data by a high resolution model of the Pacific Ocean. Proceedings of the 3rd World Meteorological Organization international symposium on assimilation of observations in meteorology and oceanography, Quebec City, Canada, (in press).
- Wallcraft, A.J., 1991: The Navy Layered Ocean Model users guide. NOARL Report 35, Nav. Res. Lab., Stennis Space Center, Miss., 21 pp.
- Wallcraft, A.J. and D.R. Moore, 1997: The NRL Layered Ocean Model. *Parallel Computing*, 23, 2227-2242.

Ability of Altimetry SSH to Constrain Highly Eddy-resolving Ocean Model

Tested by assimilation of error free SSH into the NRL 1/16° Pacific Ocean Model



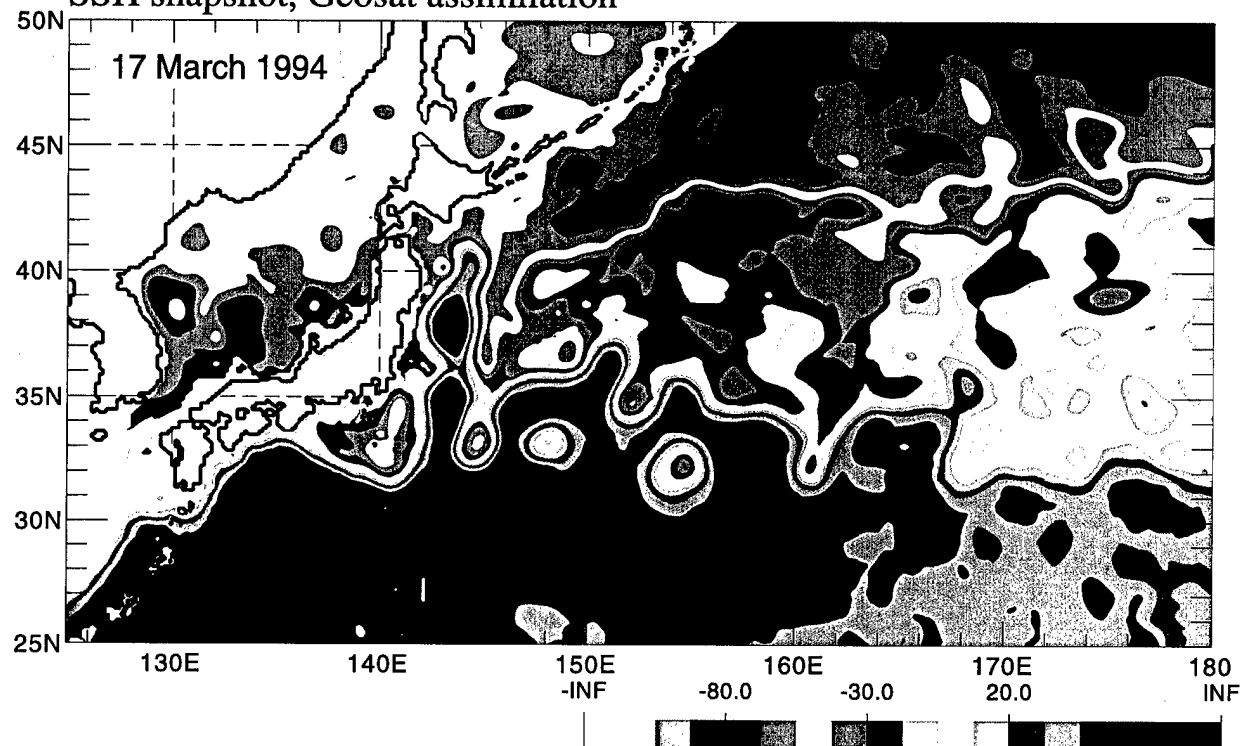
Control run (CR) was forced 1990-1998 using 12 hrly FNMOC winds. Many ocean features take > 75 days to respond to wind forcing or they are nondeterministic response to forcing.

Figure 1

Ability of Altimetry SSH to Constrain Highly Eddy-resolving Ocean Models

Tested by assimilation of error free SSH into the NRL 1/16° Pacific Ocean Model

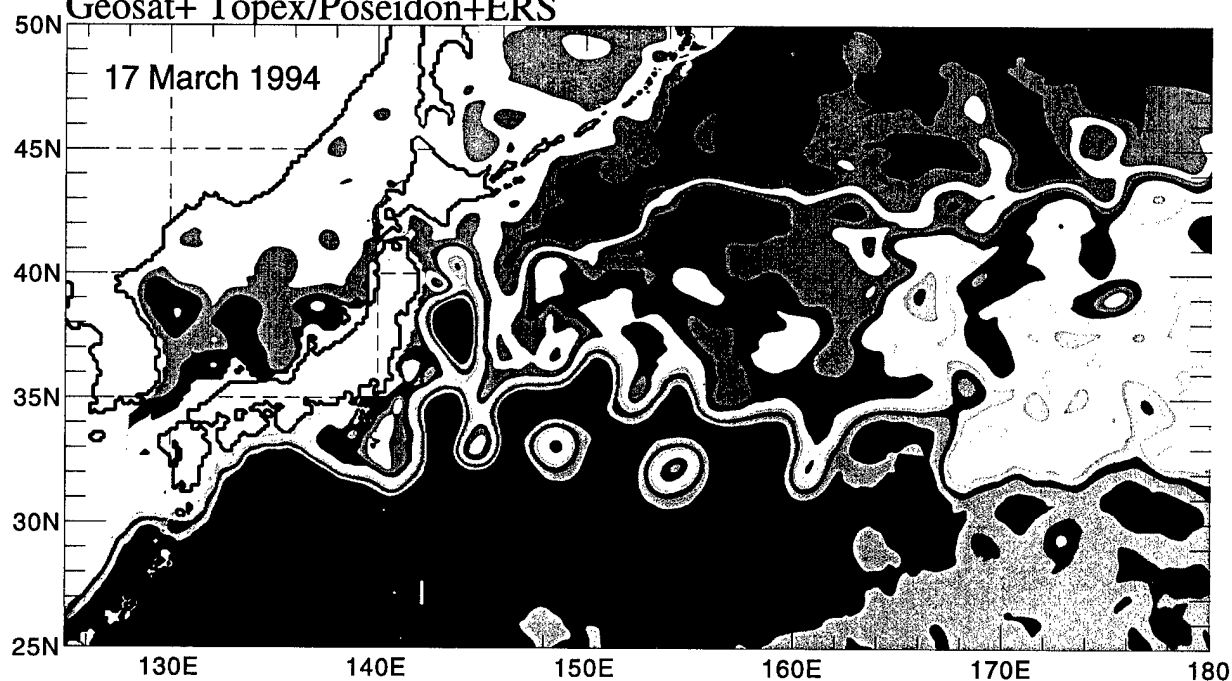
SSH snapshot, Geosat assimilation



SSH snapshot, 3 altimeter assimilation

CI = 12.5 cm

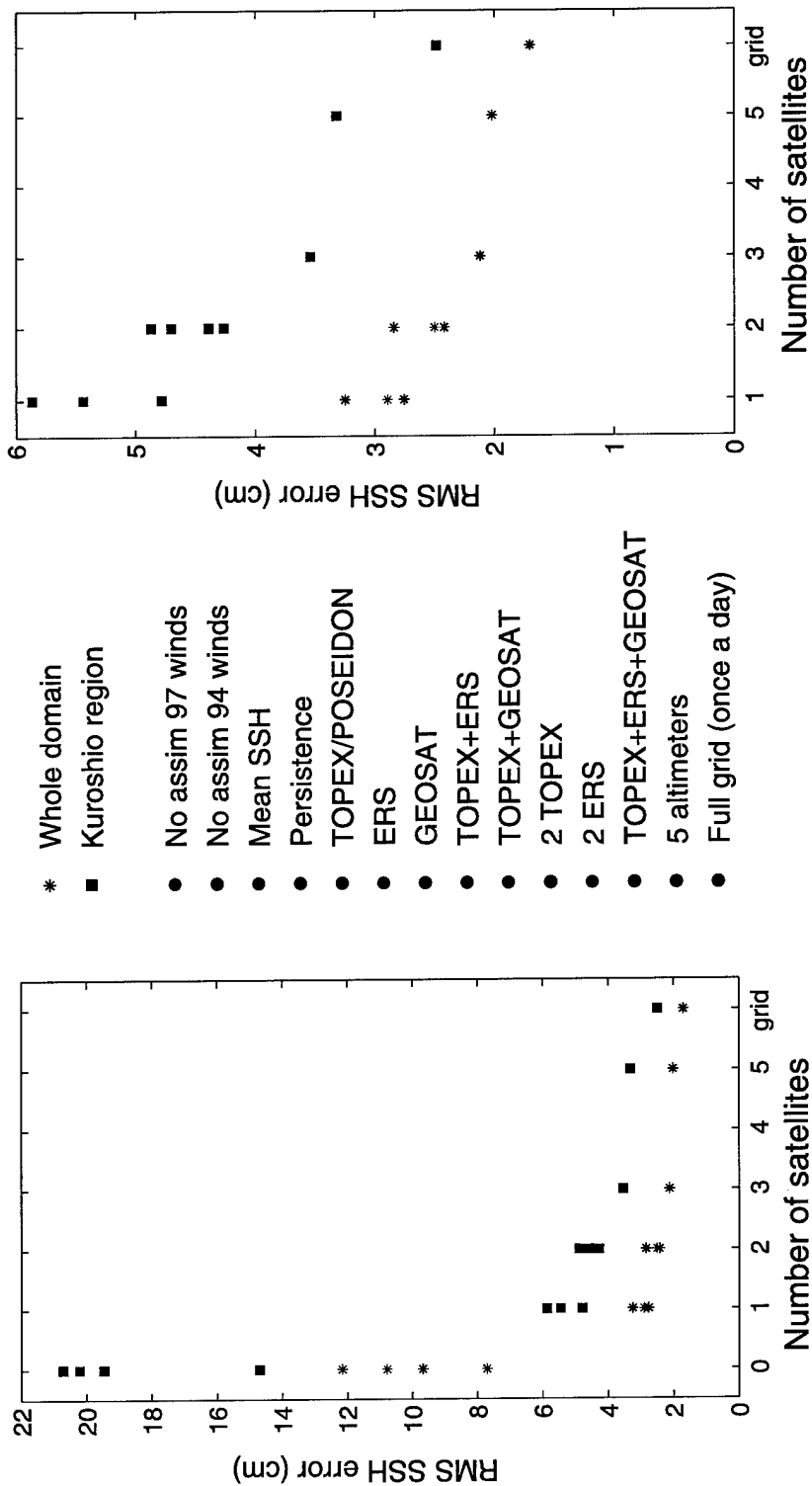
Geosat+ Topex/Poseidon+ERS



Control run (CR) was forced 1990-1998 using 12 hrly FNMOC winds. Starting from a 1997 CR initial state, 1994 wind forcing and simulated CR altimeter data from 1994 was assimilated for 80 days to make the model in 1997 look like the model CR in 1994.

Figure 2

RMS Sea Surface Height (SSH) Error vs # of satellite altimeters used in Assimilation of Error Free SSH into the NRL 1/16° Pacific Ocean Model.



Test of altimeter data capability to constrain a realistic highly eddy-resolving ocean model. Control run (CR) was forced 1990-1998 using 12 hrly FNMOC winds. Starting from a 1997 CR initial state, 1994 wind forcing and simulated CR altimeter data from 1994 was assimilated for 80 days to make the model in 1997 look like the model CR in 1994. Many features take > 80 days to respond to wind forcing or are nondeterministic response to forcing SSH RMSE is the value over the last 30 days of assimilation. The right panel is the same as the left except that "0" satellites is omitted and the ordinate is expanded to better show the impact of increasing the number of satellites.

Figure 3

Normalized RMS pressure error as a function of time
Assimilation of simulated Geosat data into
the NRL 1/16° Pacific Ocean Model

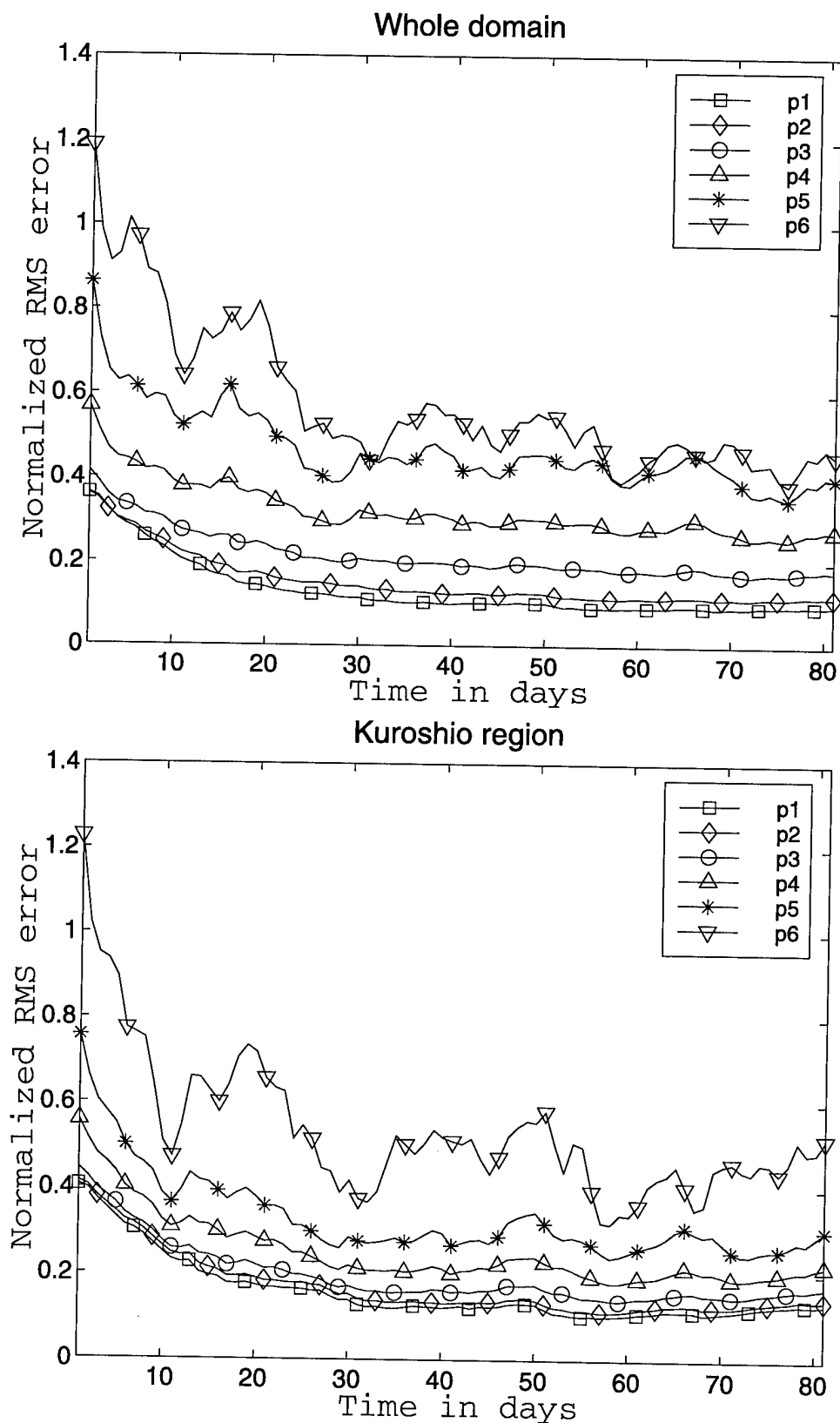
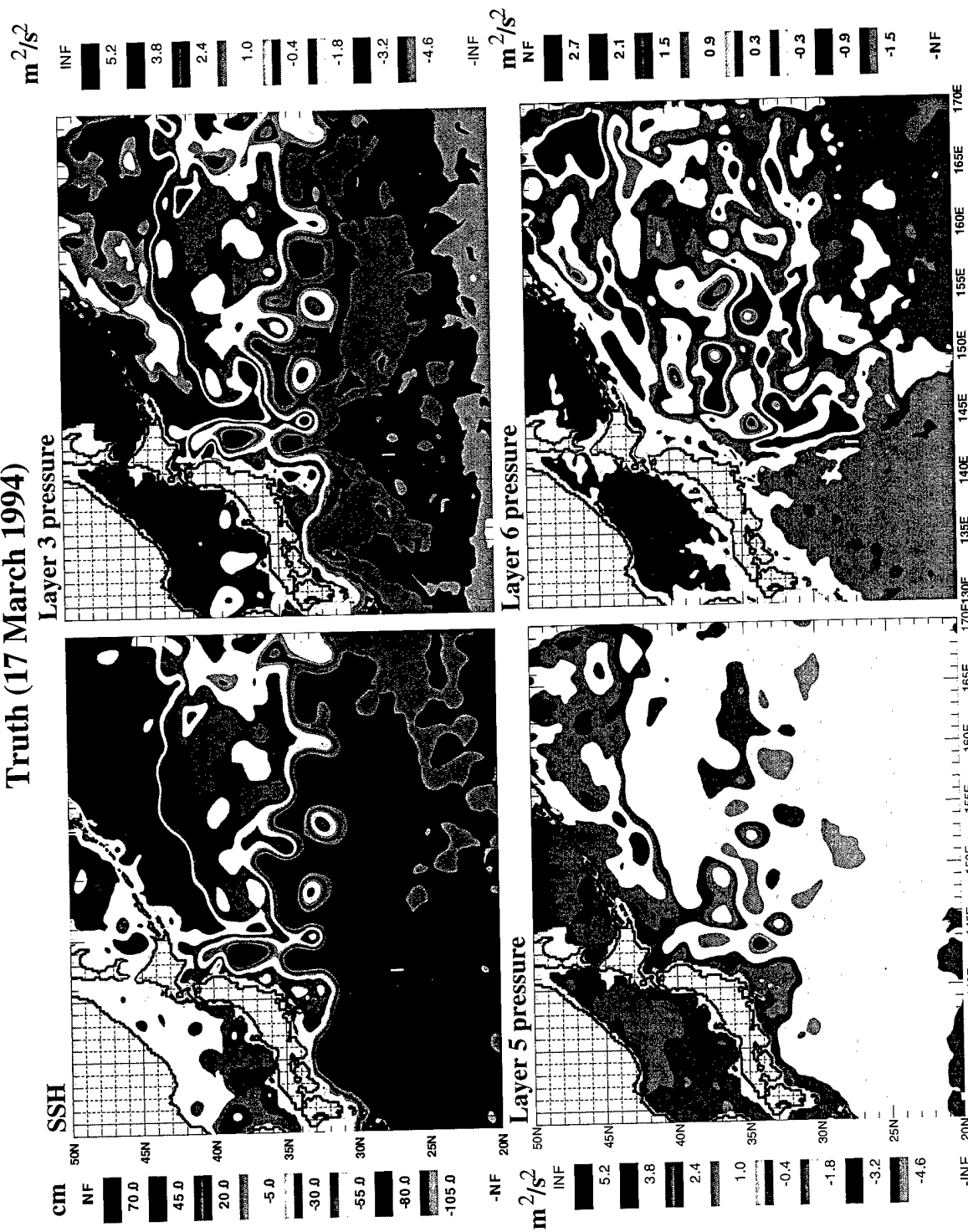


Figure 4

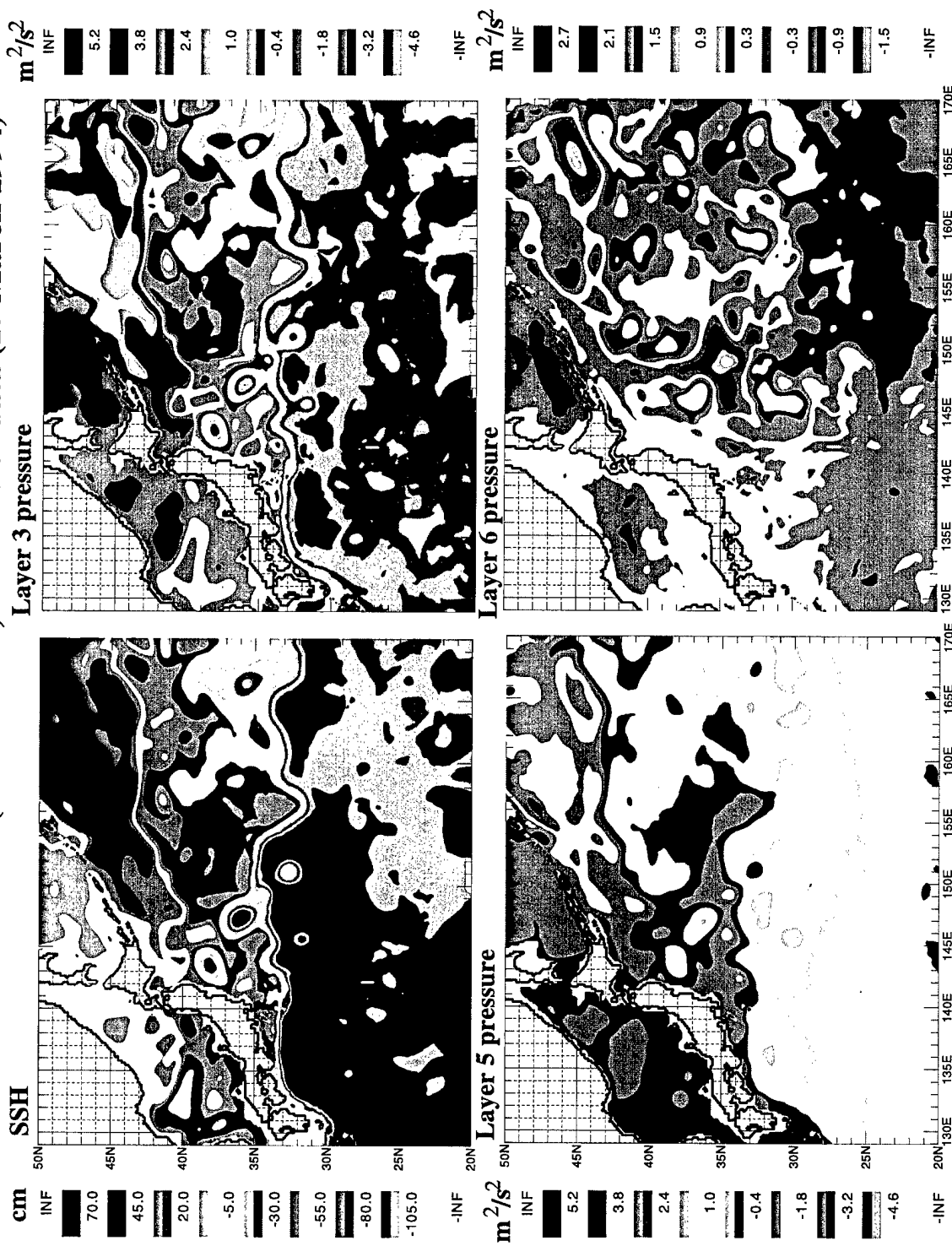
SSH and pressure from the 1/16° Pacific NLOM Truth (17 March 1994)



Forced with the FNMOC/HR hybrid winds

Figure 5

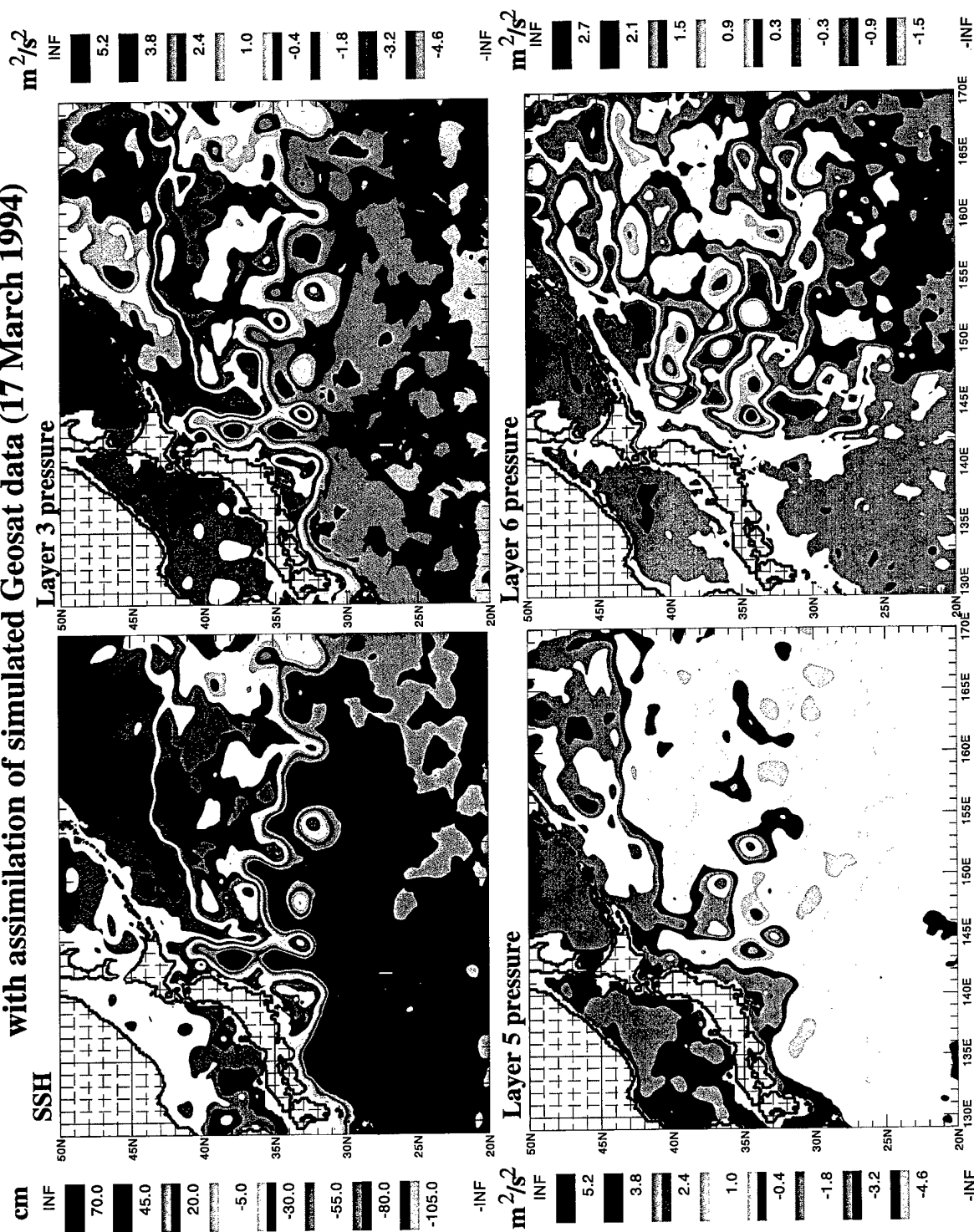
SSH and pressure from the 1/16° Pacific NLOM
with no assimilation (correct wind) of altimeter data (17 March 1994)



Forced with the FNMOC/HR hybrid winds

Figure 6

SSH and pressure from the 1/16° Pacific NLOM with assimilation of simulated Geosat data (17 March 1994)



Forced with the FNMOC/HR hybrid winds

Figure 7

1/16° Pacific NLOM SSH with Direct Assimilation of TOPEX + ERS-2 Altimeter Data

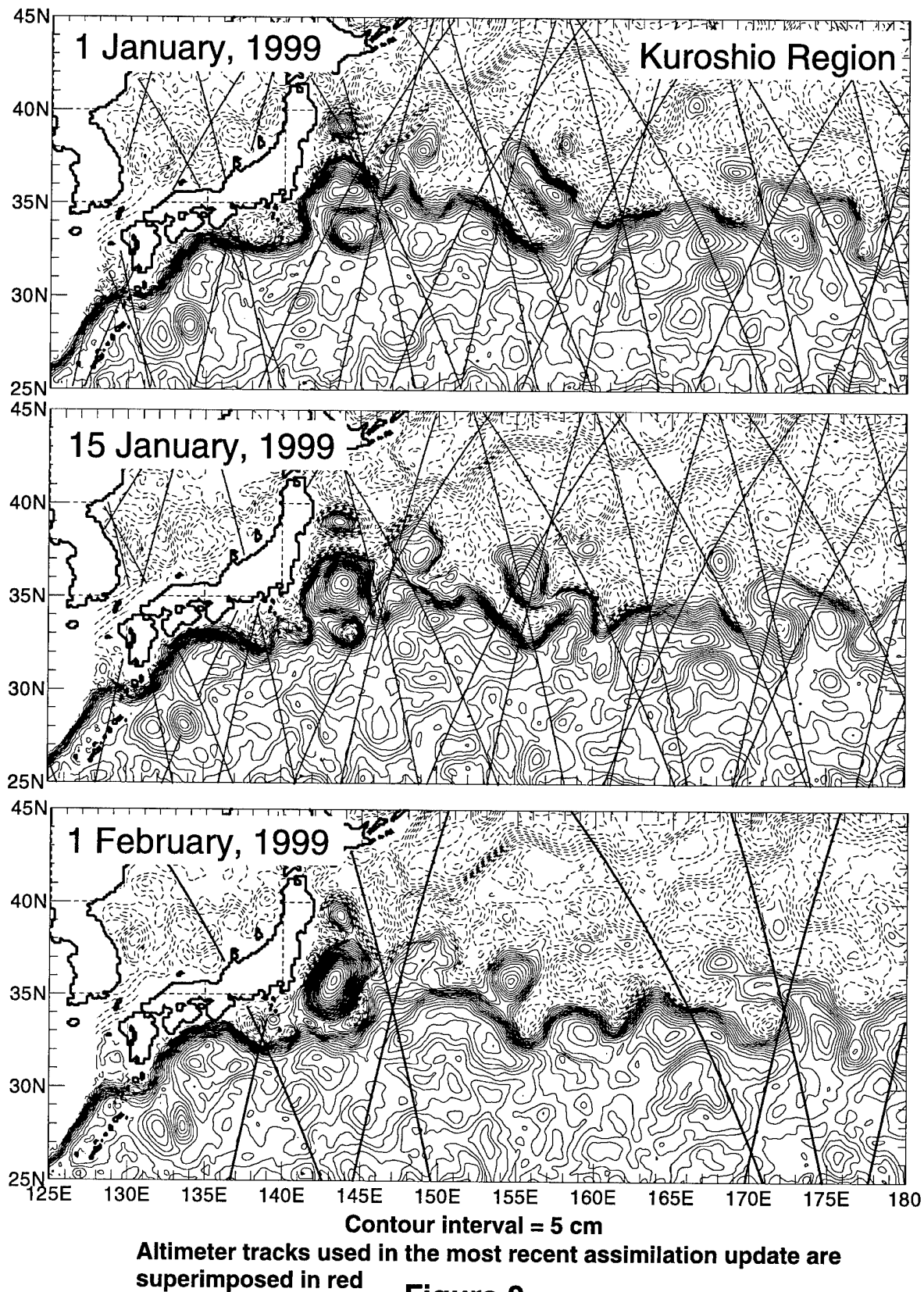


Figure 8

1/8° MODAS SSH Analyses of TOPEX + ERS-2

Altimeter Data

Mean SSH from MODAS surface dynamic height climatology

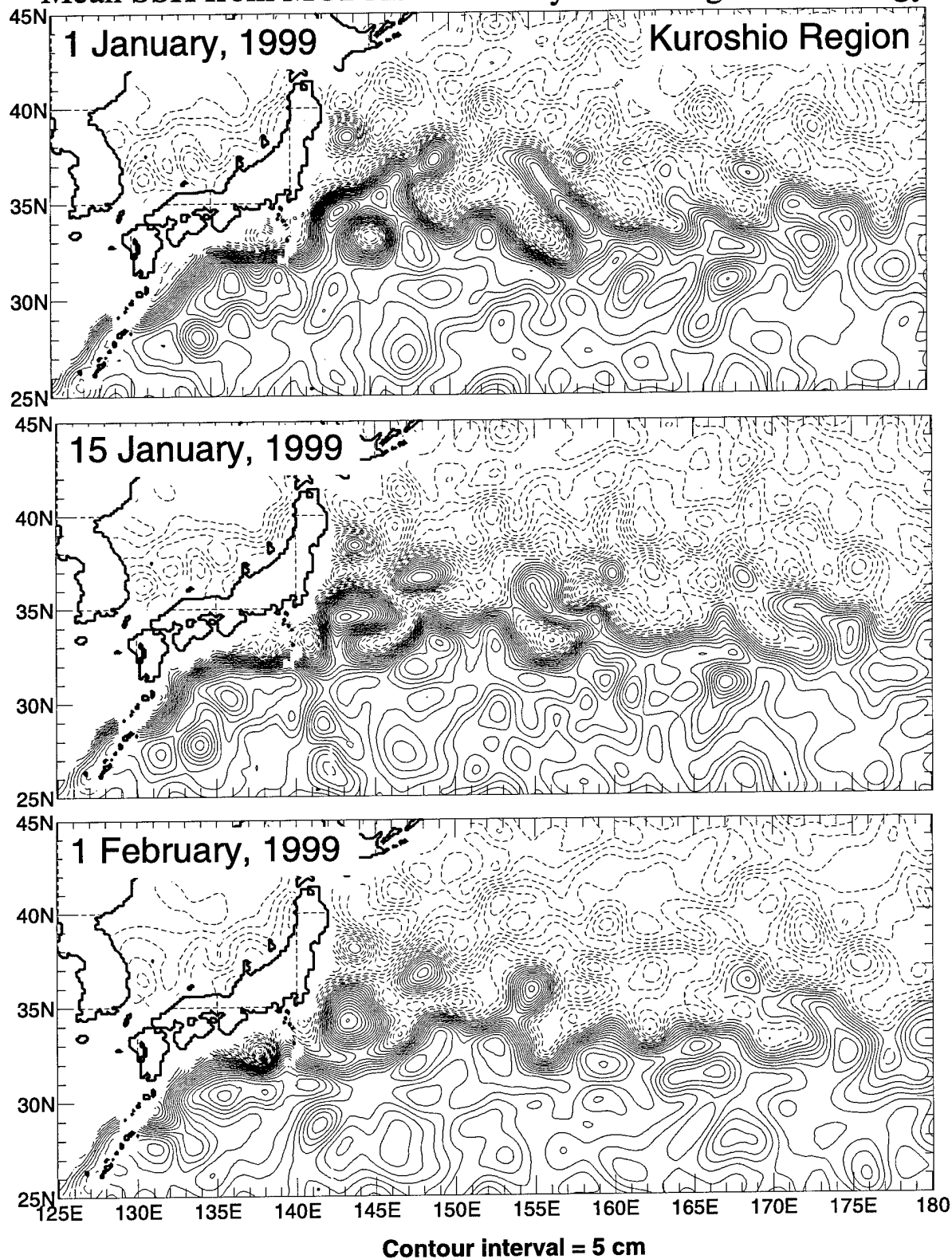


Figure 9

1/8° MODAS Sea Surface Temperature Analyses

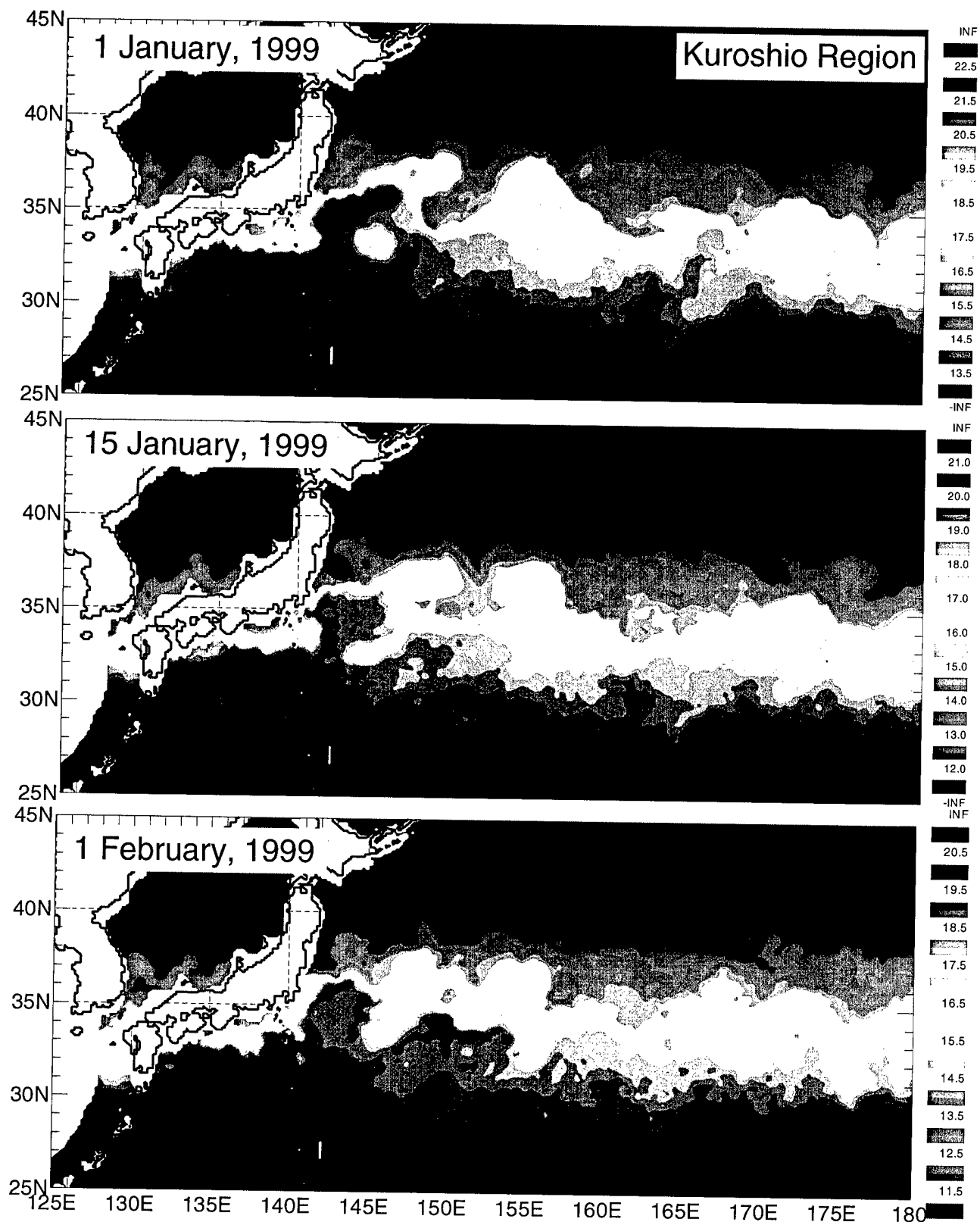


Figure 10

1/4° Global NLOM SSH with Direct Assimilation of TOPEX + ERS-2 Altimeter Data

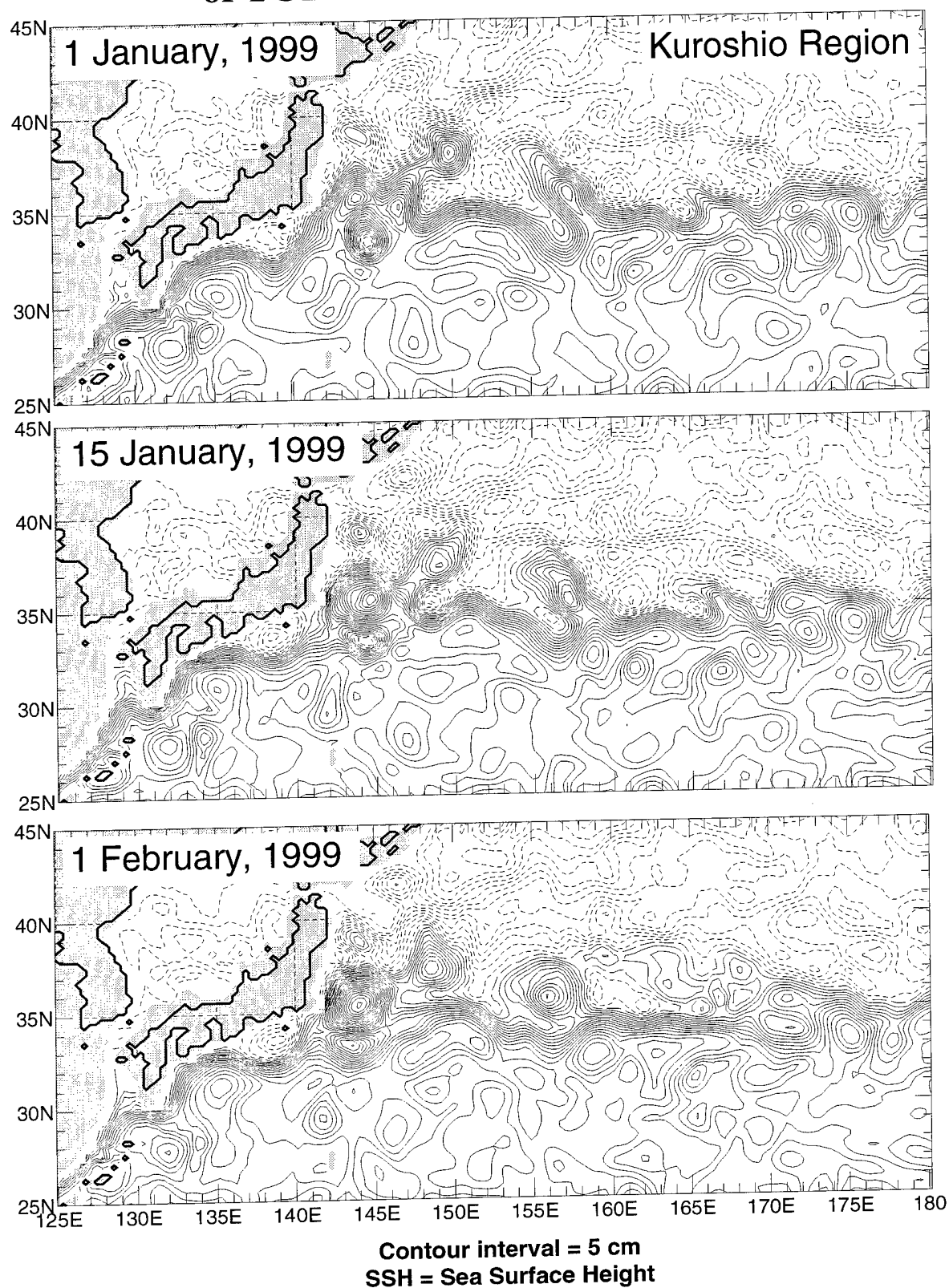
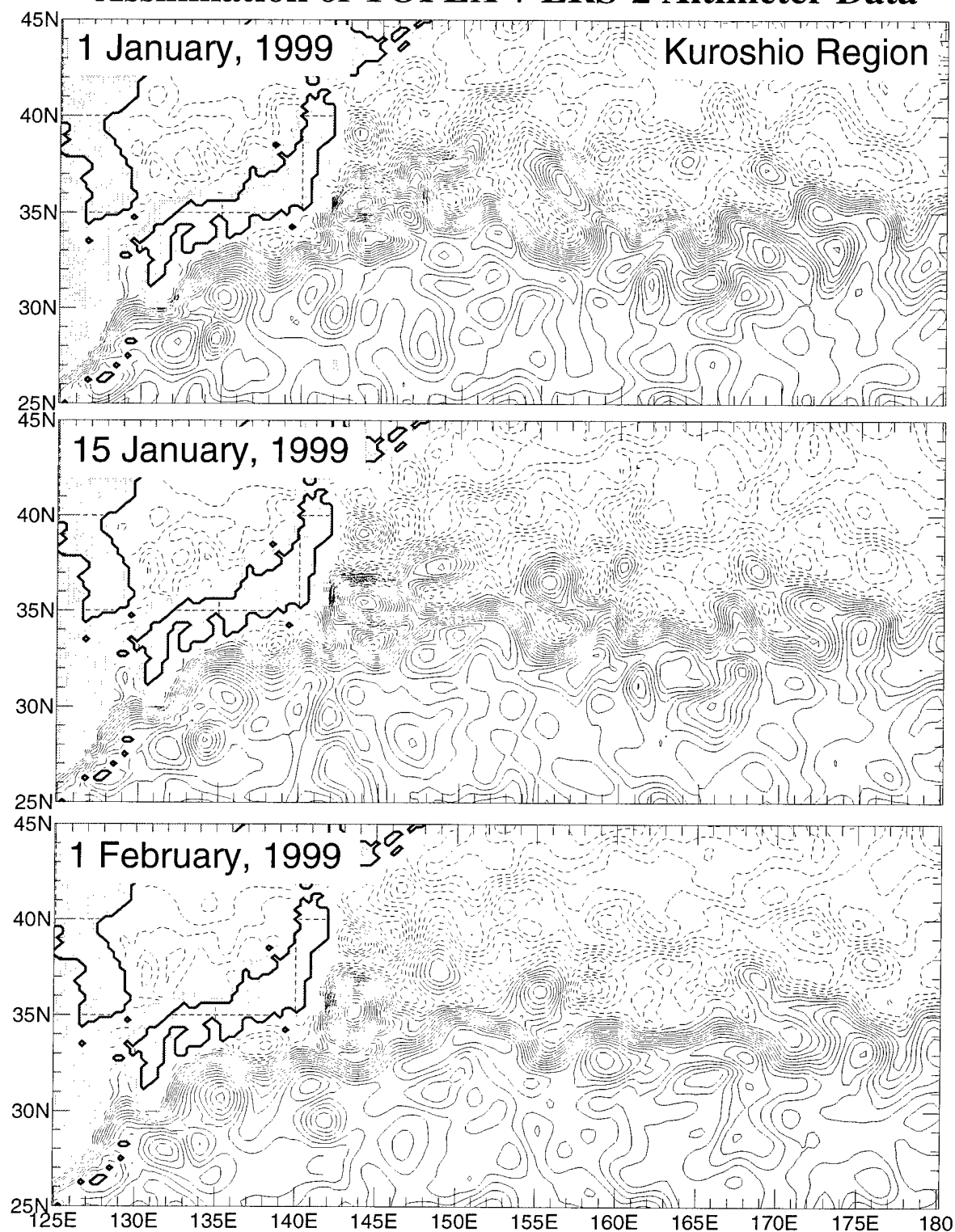


Figure 11

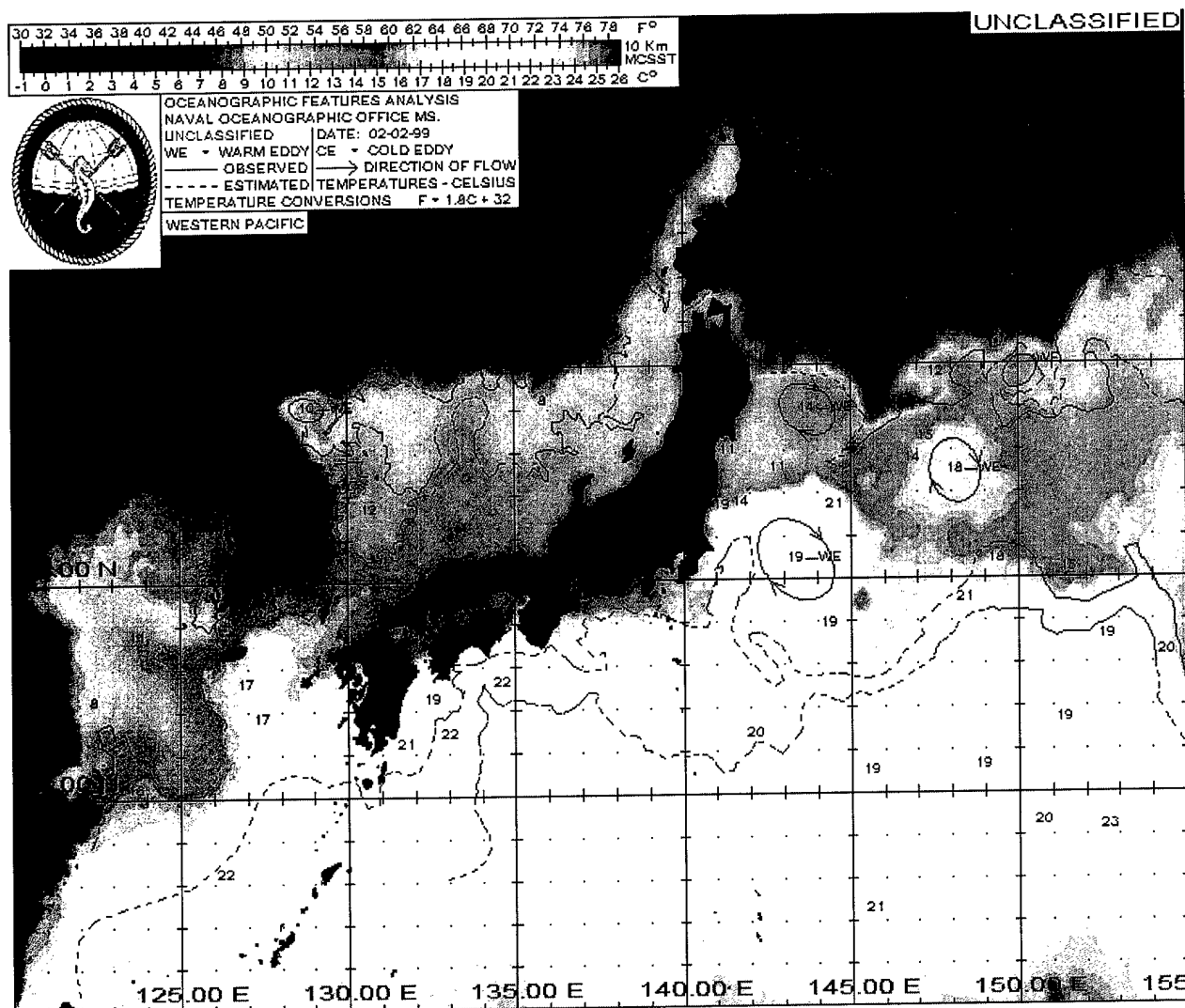
1/4° Global NLOM SSH with MODAS SSH Analyses Assimilation of TOPEX + ERS-2 Altimeter Data



Contour interval = 5 cm
SSH = Sea Surface Height. Modified model mean used with MODAS anomalies.

Figure 12

NAVOCEANO WSC Frontal Analyses for Kuroshio

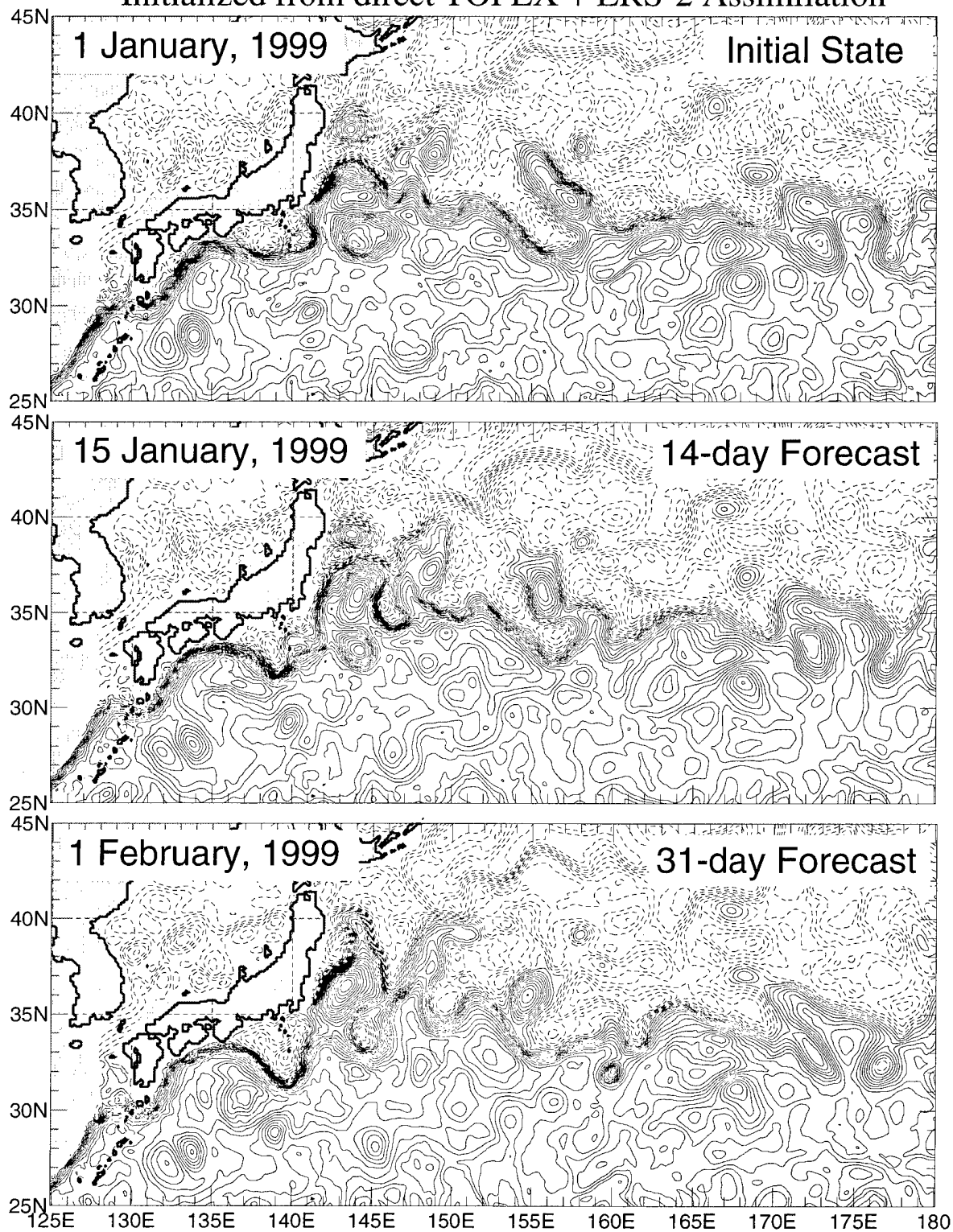


2 February, 1999

Figure 13

1/16° Pacific NLOM SSH 14 and 31 day Forecasts in the Kuroshio Region

Initialized from direct TOPEX + ERS-2 Assimilation



Contour interval = 5 cm
SSH = Sea Surface Height

Figure 14

1/4° Global NLOM SSH 14 and 31 day Forecasts in the Kuroshio Region

Initialized from direct TOPEX + ERS-2 Assimilation

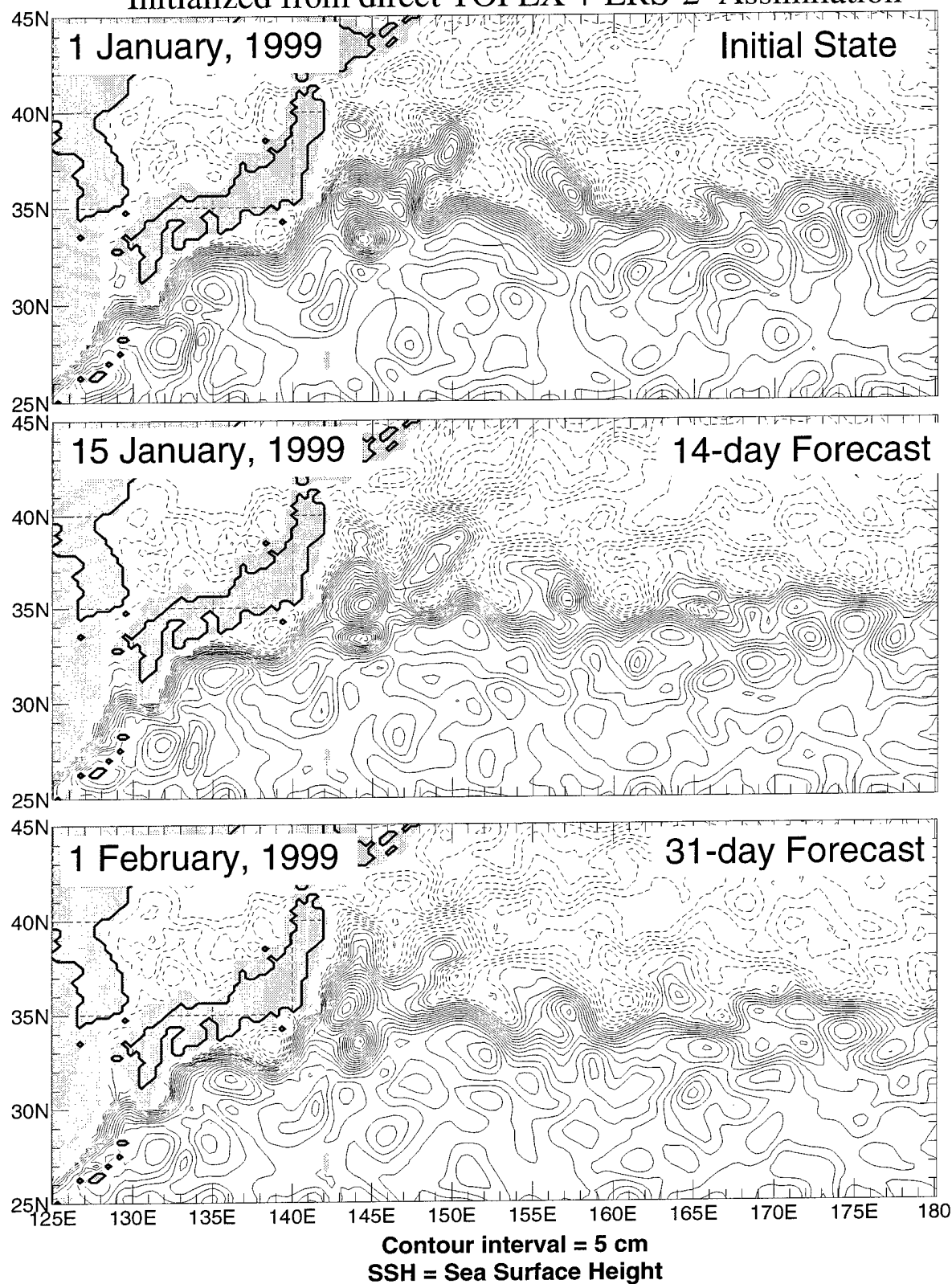


Figure 15

1/4° Global NLOM SSH 14 and 31 day Forecasts in the Kuroshio Region

Initialized from MODAS SSH Analyses Assimilation

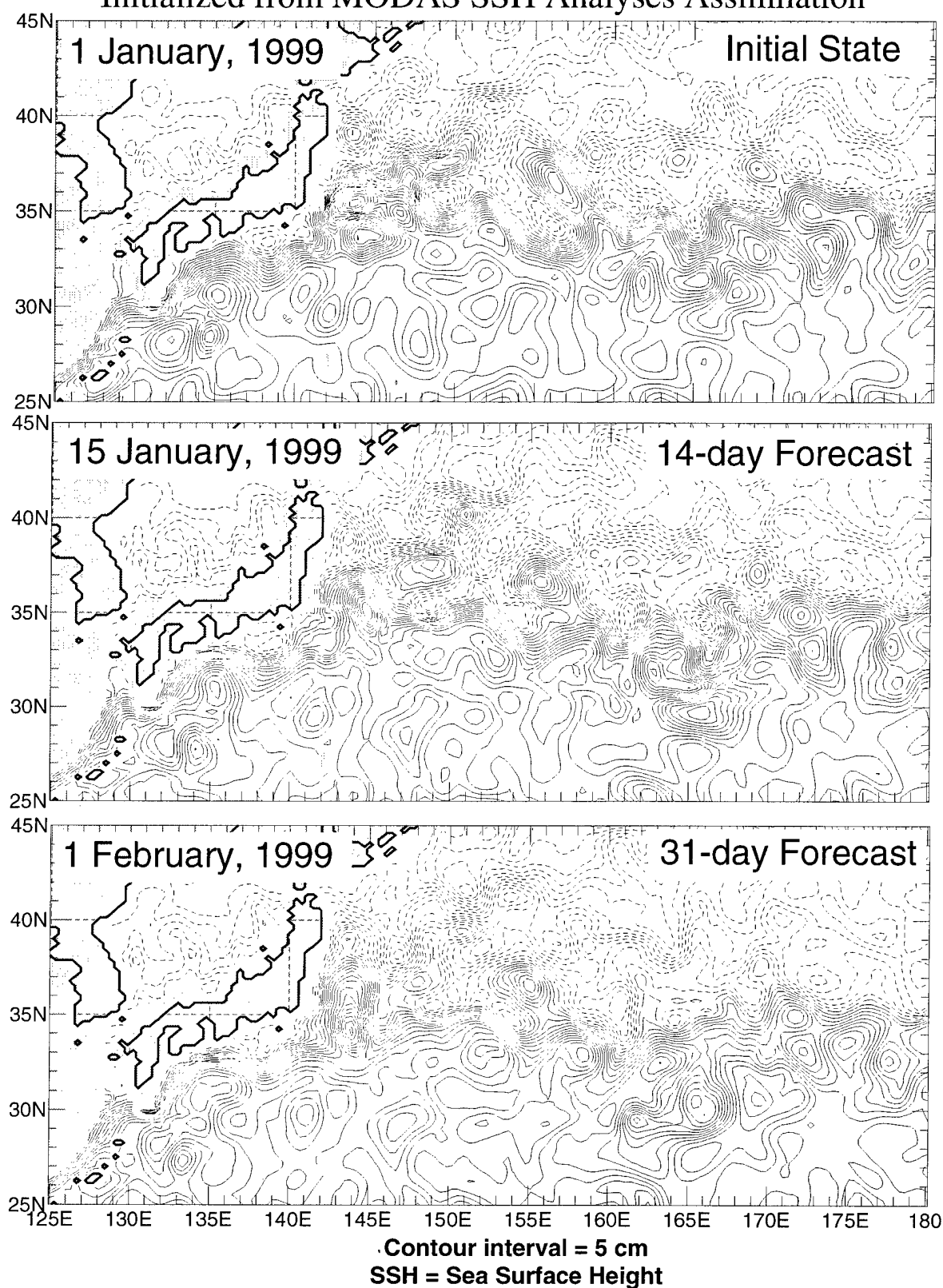
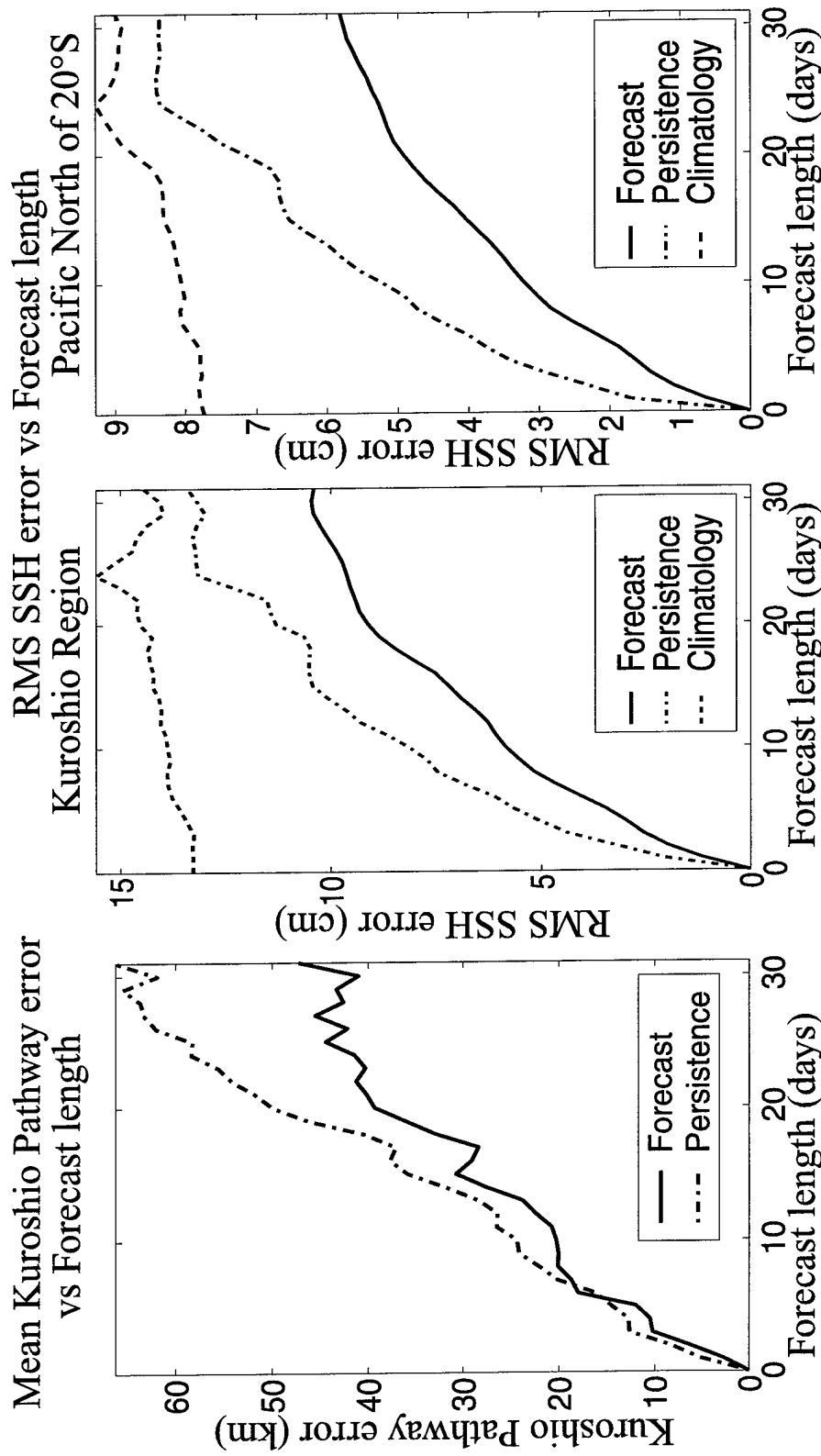


Figure 16

1/16° Pacific SSH Forecast Verification against Model with TOPEX+ERS-2 Direct Altimeter Data Assimilation

Forecast Initialized from 1 Jan 1999



Persistence: Forecast of no Change from initial state
Mean Kuroshio Pathway Error: Area between observed and forecast contours
divided by the length of the observed contour

Figure 17